SPH propagation modeling of debris avalanches along engineered slopes

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ABSTRACT

The paper deals with different examples of slopes engineered with the purpose of reducing the negative impacts of flow-like landslides. The study area is that of the pyroclastic soils, originated by the eruptions of the Vesuvius volcano, which are present over 3,000 km² in the Campania region (Italy). Debris avalanches are analyzed in conjunction with different control works positioned along the slopes such as baffles or anti-erosion installations. Aware of the limitations which still exist in the proposed numerical modelling, the overall features of the simulated flows are discussed with special emphasis on the beneficial effects and drawbacks of each type of control work.

1 INTRODUCTION

Hungr et al. (2014) define a “debris avalanche” as a “very rapid to extremely rapid shallow flow of partially or fully saturated debris on a steep slope, without confinement in an established channel”. Debris avalanches represent a global hazard responsible for large numbers of casualties and widespread damage (Schuster and Highland, 2007). The propagation of debris avalanches depends on the interplay of complex mechanisms such as bed entrainment, lateral spreading and water pressure consolidation. Cascini et al. (2012) and Cuomo et al. (2014) highlighted that bed entrainment plays a major role either inside channels or along open slopes as it increases the volume and reduces the velocity of debris avalanches, also altering the propagation pattern. However, the run-out distance and velocity are also affected by the initial value of pore water pressure and how it changes in space and time due to vertical consolidation (Pastor et al., 2009).

Nowadays, debris-resisting structures are often used as defense measures to retain landslide debris and limit the debris mobility (Mizuyama, 2008). The protection measures may include rigid and flexible barriers (Wendeler et al., 2007), levees, slit dams (Watanabe et al. 1980), arrays of baffles or erosion control works. The main function of these countermeasures is to block, stop or deflect the flow and so protect the downstream facilities. In this paper, differently engineered slopes are analysed aiming to provide discuss some mitigation options and current modelling potential.

2 MATERIALS AND METHODS

The “GeoFlow_SPH” model proposed by Pastor et al. (2009) was used, which schematises the propagating mass as a mixture of a solid skeleton saturated by water. The unknowns are the velocity of the solid skeleton and the pore water pressure. The Smoothed Particle Hydrodynamics (SPH) numerical technique discretises
the propagating mass through a set of moving “particles”, to which the unknowns and their derivatives are linked. The model assumes that pore water pressure dissipation takes place along the normal to ground surface; the velocity of the solid skeleton and pressure fields are computed as the sum of two components related to two separate processes: propagation and consolidation. The governing equations are integrated along the vertical axis, and the resulting 2D depth-integrated model presents an excellent balance of accuracy and simplicity. The potential of this approach is appreciable for the flow-like landslides, which have small average depths in comparison to their lengths and widths. The entrained material is assumed with nil velocity and nil pore-water pressure when entrained by the propagating mass. The erosion rate is defined as a time derivative of the ground surface elevation when other causes are not in play. Once the entrainment rate has been assigned, the amount of bed entrainment, the cumulative value of the erosion rate over time, or eroded depth, depends on both the height and velocity of the propagating mass and the time duration of the flow at each point on the landslide path. An empirical law for entrainment rate (Blanc et al., 2011) was used, which assumes the entrainment rate as function of soil propagation height, velocity, local slope angle and an empirical coefficient ($K_r$) to be calibrated (Pastor et al. 2007; Blanc et al. 2011; Cascini et al., 2014, 2016; Cuomo et al., 2014, 2016).

Several analyses were carried on a schematic open slope, consisting of two planes with inclines to the horizon $i_1$ and $i_2$, respectively (Fig. 1a). The failed volume was located at the uppermost edge of the upper slope, inside the so-called source area from which the material slips down. Along the flow path two rows of rectangular vertical obstacles (baffles) have been positioned (Fig. 1b), or two anti-erosive installations with nil erosion imposed inside (Fig. 1c).

Figure 1: Open slope scheme (a) equipped with baffles (b); anti-erosive installations (c).

4. NUMERICAL RESULTS FOR DIFFERENT CONTROL WORKS

4.1. Baffles

SPH analyses were carried out considering two rows of baffles placed on the upper zone of the slope with the aim to understand how these obstacles can change the dynamic of the debris avalanche, considering the erosion height and the mobilized volume. Obstacles has a general positive effect against landslide propagation. Both upstream and downstream there is a significantly reduction in the erosion height. This is because when the flow interacts with the obstacles it diminishes its velocity and so also the erodible capacity of the landslide. In Fig. 3 the blue line is the initial longitudinal profile of the slope, in red line the profile after the propagation of the debris avalanche, and as green line how the erosion height change all over the slope. This is the “local-specific” effect of landslide propagation combined to bed entrainment, since the erosion height changes differently in any longitudinal section. Besides that, the obstacles along a slope has also a “global” positive effect, that is to say a reduction in the mobilized volume of the debris avalanche.

4.2. Anti-erosive installations

In this case, the SPH analyses were carried out considering two different installations, one placed on the upper zone of the slope, and another in the zone where the erosion is more relevant. The results (Fig.4) are represented analyzing the same control variables used for the case of baffles in order to have a similar
comparison between the two different types of control works. Analyzing the longitudinal profile (Fig. 4b), it is simple to note an increase of the erosion height just downstream the anti-erosive zones. This is because when the flow passes over these zones, as it does not receive the brake-effect of the bed entrainment, it increases its velocity.

To discuss this issue, the amplification factor \( A_f \) can be considered, defined as the ratio of the final mobilised volume \( (V_f) \) and the initial volume \( (V_i) \). The amplification factor was plotted step by step for the simulation (Fig. 5). The most significant achievement of anti-erosive installations is not to reduce the maximum value of the erosion height, but to reduce the volume of the landslide and the quantity of material that reaches the deposition zone.

Figure 2: erosion heights for: a) engineered slope with baffles; b) natural slope.

Figure 3: longitudinal erosion profiles for: a) engineered slope with baffles; b) natural slope.

Figure 4: Engineered slope with anti-erosive installation: a) erosion heights; b) longitudinal erosion profile.
3 CONCLUSIONS

A simple slope scheme was analyzed, consisting in two planes with different inclination angles. Along the propagation path two different control works were considered for reducing the effects of debris avalanches. Independent on the selected type of intervention, a (local or generalized) reduction of bed entrainment and total landslide volume was simulated. This effect corresponds to a reduction of runout distance, and eventually to reduced lateral spreading of flowing materials.

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REFERENCES